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*Coastal subsea permafrost and bedrock
observations using dc resistivity*

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Cover: Deploying a floating cable in Prudhoe Bay.

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Coastal subsea permafrost and bedrock observations using dc resistivity

Paul V. Sellmann, Allan J. Delaney and Steven A. Arcone



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| <p>Measurements were made at several New England coastal sites and at three sites in Prudhoe Bay, Alaska, to evaluate dc resistivity techniques for mapping resistive seabed features: bedrock and subsea permafrost. The field studies employed the four-probe Wenner array technique, with electrode separations up to 50 m. The New England sites were selected to simulate permafrost conditions to help establish a feeling for the range of apparent resistivity in areas of sub-sea permafrost, and for information on the vertical and lateral resolution of the technique. At Prudhoe Bay, offshore measurements were made with a floating cable, and inland measurements were made using electrodes driven into the ground. These observations indicate that the electrical properties of permafrost beneath the coastal bluff and adjacent tundra are rapidly modified by coastal erosion and periodic flooding during storms. Maximum apparent resistivity at the water's edge was around 50 Ω-m, and at distances greater than 100 m from shore all values were less than 20 Ω-m. Modeling supported by the drilling data permitted an interpretation of the position of the top of ice-bonded subsea permafrost. Real resistivities for the ice-bonded permafrost ranged from 200 to 1000 Ω-m. The technique and equipment used for this study appear to have applications for studies in shallow coastal waters where permafrost is not more than 30 m below the seabed and where water depths do not exceed 6 to 7 m.</p> | | | |
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PREFACE

This report was prepared by Paul V. Sellmann, Geologist, Civil and Geotechnical Engineering Research Branch, Experimental Engineering Division; and Allan J. Delaney, Physical Science Technician, and Dr. S.A. Arcone, Geophysicist, both of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for the research was provided by DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions*; Technical Area D, *Cold Regions Base Support Design and Construction*; Work Unit 001, *Electromagnetic Geophysical Methods for Rapid Subsurface Exploration*. Initial work was funded by the U.S. Department of Energy, Arctic Energy Technology Program.

The authors thank Ronald Atkins and Dr. Donald Albert for their interest in this work and their helpful technical reviews. This report covers observations made as part of CRREL's investigations of marine dc resistivity techniques for obtaining information on subsea permafrost in Arctic coastal waters.

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Coastal Subsea Permafrost and Bedrock Observations Using dc Resistivity

PAUL V. SELLMANN, ALLAN J. DELANEY AND STEVEN A. ARNONE

INTRODUCTION

Background

Engineering and research investigations conducted in shallow coastal waters often depend on geophysical techniques to help define bottom conditions. Seismic techniques have commonly been used to determine layering, changes in sediment type and depth to bedrock. However, there are problems with noise in shallow water and there is high attenuation of energy where sediments contain gas. Because of these problems, and the lack of an established method to obtain information on the depth to the top of shallow ice-bonded permafrost in Arctic coastal waters, we initiated this study using dc resistivity techniques.

Early geophysical investigations of permafrost used dc resistivity methods to determine its distribution on land (Joesting 1941, Barnes and McCarthy 1964). More recent and concurrent development work (Scott 1975, Corwin 1983, Dyck et al. 1983, Sellmann et al. 1985, Scott and Maxwell, in press) indicated that the dc resistivity technique could also be used in shallow coastal waters (less than 30 m) to delineate seabed features. The dc method, with its potential for good resolution at shallow depths, can complement deeper-sounding Transient Electromagnetic Methods (TEM) (Ehrenbard et al. 1983, Walker et al. 1985). Studies by the Earth Technology Corp. (1985, 1986) have suggested that modified TEM equipment and procedures, and Magnetic Induction (MI), might also be used for investigations at shallow depths below the seabed. At present, it appears that a combination of dc and TEM is the most practical geophysical approach to obtaining information on the entire offshore permafrost section.

Researchers interpret resistivity data by attempting to construct layered models of the subsurface that produce resistivity profiles that match field observations. Closed-form inversion solutions are virtually impossible to achieve; therefore, computational programs utilizing fast iterative

procedures are now commonly used to produce a layered model to fit the data. These programs require estimates for the resistivity and thickness of each assumed layer. Resistivity data have been correlated with subsurface sections having a known distribution of ice-bonded permafrost. However, much of this information is proprietary. Near-shore resistivity data are also lacking because researchers have limited experience with shallow-penetrating electrical methods in areas of ice-bonded subsea permafrost; this is one of the reasons for this study.

The electrical properties of subsea permafrost may undergo substantial change in coastal settings. Inundation can dramatically change the properties of permafrost by exposing it to salt water and warming it by as much as 10°C. Most subsea permafrost was formed on the continental shelves when they were exposed during periods of low sea level associated with times of major glacial activity. This permafrost was then covered by rising sea level as the glaciers melted. Even though sea level is now fairly stable, permafrost is still being inundated in areas of active coastal erosion.

Objectives and approach

Our objective was to see if dc techniques could be applied to seabed studies in shallow coastal waters to obtain information on the distribution of bedrock and subsea permafrost. If the technique appeared promising, we would attempt to map the top of ice-bonded permafrost and establish resistivity values for permafrost in areas of active coastal erosion. These data would also be important for future interpretation of electrically based methods.

The initial experimentation was done at coastal sites in New England to obtain field data in support of modeling, thus illustrating the influence of water depth on observations made with a floating cable and a low power system. The results encouraged us to construct a long, floating Wenner array

and test the system on subsea bedrock features previously mapped by seismic methods and drilling in the New Haven, Connecticut, Harbor (U.S. Army Corps of Engineers 1981). This site was also selected since the geologic setting (mud over bedrock) provided a good electrical approximation of bottom conditions in an area of subsea permafrost.

Positive results at the New Haven site led to the studies near Prudhoe Bay, where ice-bonded permafrost is known to exist at shallow depths below the seabed. Several sites with different coastal relief and beach configuration were studied. We assumed that the general distribution of subsurface materials would be similar at all study sites and that coastal erosion rates were approximately 1 m/yr. We collected data on land with dc soundings made parallel to the shoreline, using electrodes driven into the ground. Observations extended progressively inland beyond any evidence of flooding of the tundra surface. We varied the spacings between soundings on land to provide coverage of local relief and features found on the beaches, bluffs and adjacent tundra surfaces. The farthest inland soundings were considered references, representing subsurface electrical properties not yet modified by coastal processes, and were made on what appeared to be undisturbed tundra surfaces. A floating cable was used to extend the survey lines up to 2.8 km offshore by profiling and sounding at regular intervals from the beach. The cable was normal to the shoreline for most of this surveying.

DC SOUNDING METHOD

Resistivity was measured using the Wenner array (Fig. 1), which consists of four colinear, equispaced electrodes. The two outer electrodes inject and receive current I , and the resulting gradient in potential V is measured between the inner elec-

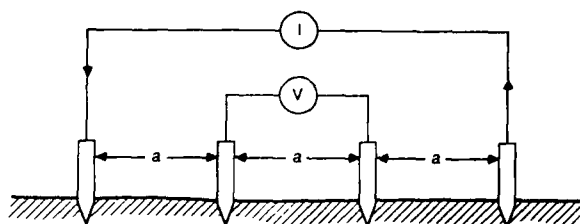


Figure 1. Multielectrode Wenner array. The electrode separation a was varied from 0.5 to 50 m on land and 3 to 50 m offshore.

trodes. For homogeneous ground, the real resistivity ρ in ohm-meters is equal to the measured apparent resistivity ρ_a , which is found from the formula

$$\rho_a = 2\pi a \frac{V}{I}$$

where a is the interelectrode spacing. Over layered earth, ρ_a is also a function of the layer thicknesses and resistivities; therefore, it is an apparent quantity. Computational modeling must then be used to interpret the sounding curve.

Two of the CRREL cables were fabricated from standard single-conductor wire. Cable 1 was 210 m long with seven a spacings that ranged from 10 to 60 m. It was used for both bottom and floating cable measurements. Cable 2 was a short bottom-cable, 30 m long, with six a spacings that ranged from 2 to 11 m. The third cable, fabricated by a commercial cabling company, had a polyurethane outer jacket and was bouyant. It was 150 m long with eight Wenner a spacings from 3 to 46 m. The progressively larger a spacings in the Wenner array telescoped out from the end nearest the boat so that the first electrode was always in use. All of the cables used simple lead electrodes as described by von Arx (1962). These cables provided a wide range of electrode configurations and separations for both floating and seafloor measurements.

Modern equipment and operating techniques are designed to overcome two major obstacles in making dc resistivity measurements: 1) excessive resistance caused by poor contact between the electrodes and the ground, which can occur in dry, coarse-grained soil, in frozen ground or in rock, and 2) measurement interference associated with natural earth currents and potentials. Contact resistance is not a problem in the marine environment, since the electrodes are immersed in seawater. On land we used copper-clad electrodes driven approximately 15 cm into the ground at a spacings up to 50 m. The low resistivity of the thawed active layer and marine sediments on the beach ensured good electrode contact.

A regulated current signal with a total period of 32 seconds was generated by a Huntect transmitter, and potential was measured with a Fluke digital voltmeter. The Huntect unit has switch-selectable output impedance, and output current is variable to 1.5 A. In most cases the maximum output current was used for the marine surveys. An illustration of this instrumentation and one of our marine cables is shown in Figure 2.

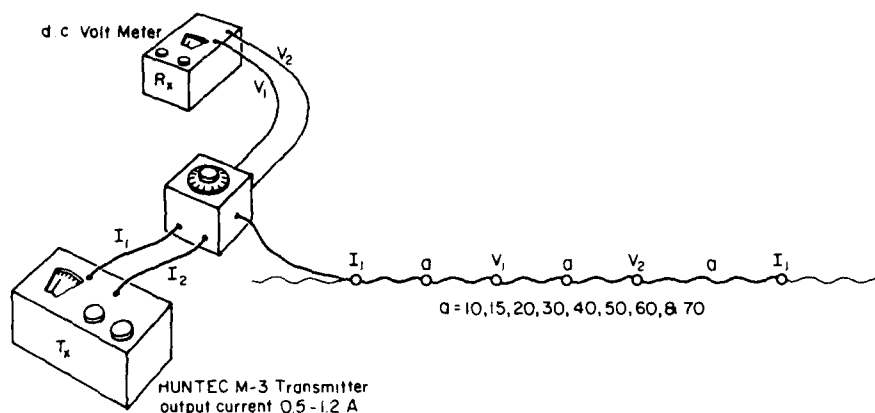


Figure 2. Generalized illustration of multiconductor cable, electrode geometry and switching equipment used for the offshore observations. Switching equipment allows selection of a separation.

COMPUTER MODELING AND INTERPRETATION

Evaluation and interpretation of data were based on the well-developed theory for resistivity sounding of layered media. We did the forward modeling used to predict the results of the earlier studies at the New England sites with the aid of theory developed by Mooney et al. (1966). The Beaufort Sea data for the later studies were inverted using a commercially available (but proprietary) program called RESIX (Interpex Limited, Golden, Colo.). Such programs have evolved from the work of Inman (1975), Zohdy (1975) and Pelton et al. (1978) for example. In the RESIX program, an approximate model with a set number of layers is continually modified by a least-squares-error procedure, providing layer thickness and resistivity values that best match the field data. There is no assurance that the model is unique, only that it is plausible if the average error between the model curve and the data points is less than about 10%.

RESULTS AND DISCUSSION

New England

Kittery and Eastport, Maine: water depth studies

Initial observations to assess equipment performance and determine the influence of water depth on resistivity values were made at Kittery and Eastport, Maine. Profiling was done in New Haven Harbor, Connecticut, since our results could be compared to the large amount of information available on depth to bedrock (U.S. Army Corps of

Engineers 1981). These sites were also selected because the seabed electrical properties were similar to those measured in some subsea permafrost zones (Corwin 1983), with the surface of resistive rock simulating the top of ice-bonded permafrost.

The sites at Kittery and Eastport were chosen because of large tidal fluctuations and accessible outcrops that enabled us to directly measure bedrock resistivity. At each site the surface sediments were underlain by metamorphic or granitic rocks that outcropped above low water. No information was available on depth to bedrock beneath the cables, but the many outcrops suggested that bedrock was near the seabed. Floating and bottom cables were secured parallel to the beach and data were recorded throughout tidal cycles from a dock. Tidal variations were about 7 m at Eastport and about 2.5 m at Kittery.

The resistivity of bedrock outcrops above high water and the resistivity of saturated sediments and bedrock exposed at low water were measured using an ac magnetic induction technique (the Geonics EM-31) (Arcone et al. 1979). The results are summarized in Table 1. The salinity of the seawater was about 30‰ and the resistivity approximately 0.2 $\Omega \cdot m$. Preliminary modeling of the Kittery site indicated that, for an array with a spacings up to 60 m, we could expect apparent resistivity to vary between about 1 and 10 $\Omega \cdot m$ throughout a tidal cycle.

We anticipated that water depth would have a significant influence on observations made in shallow coastal waters. Therefore, the response of a floating array at the Maine sites was studied both experimentally and by using a mathematical model

Table 1. Resistivity data ($\Omega\cdot m$) from shoreline observations.

| | Kittery, Maine | Eastport, Maine | New Haven, Connecticut |
|---|----------------------|------------------------|---------------------------|
| Rock outcrops above high water (1-3 m) | — | 450 to >10,000 | 67 to 313 210 avg |
| Rock outcrops exposed at low water | 18 to 100 63 avg* | 45 | 23 to 33 28 avg |
| Sediments exposed at low water | 2.4 to 4.1 | 3.4 to 7.2 5.46 avg | — |

* Average values are shown where more than 10 measurements were made.

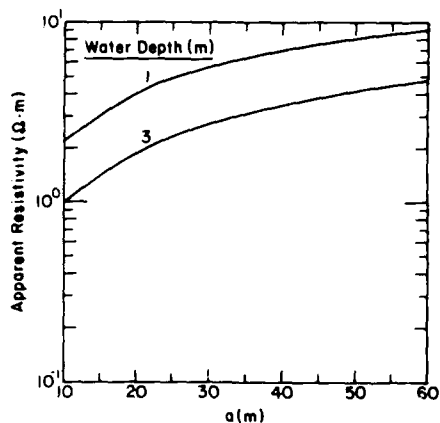


Figure 3. Model illustrating the influence of water depth on observations with a floating Wenner array for the Kittery, Maine, site. The resistivity values used were $0.25 \Omega\cdot m$ for seawater, $2.0 \Omega\cdot m$ for sand and $20.0 \Omega\cdot m$ for the rock. The thickness of the sand layer was 2.0 m.

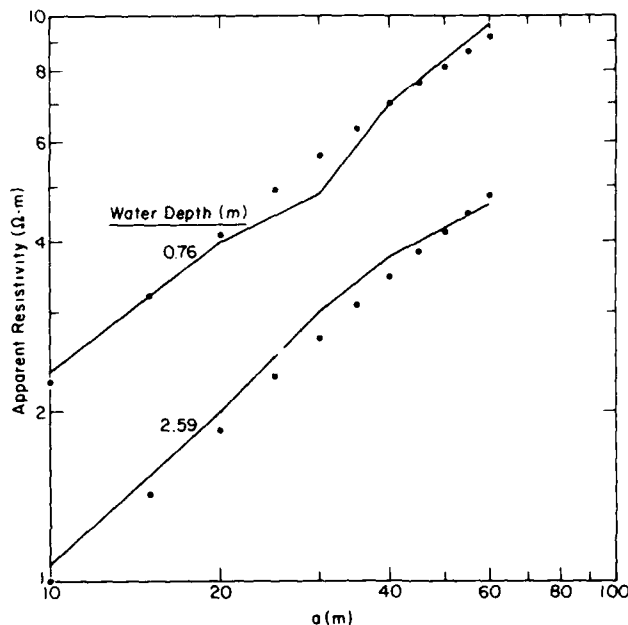


Figure 4. Apparent resistivity data obtained with a floating Wenner array at Kittery, Maine (solid lines), compared with the model data (dots) shown in Figure 3.

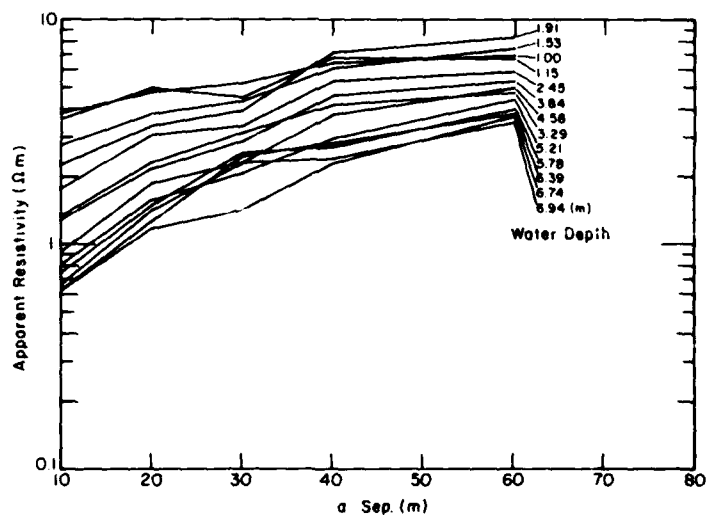


Figure 5. Apparent resistivity data obtained with a floating Wenner array at Eastport, Maine.

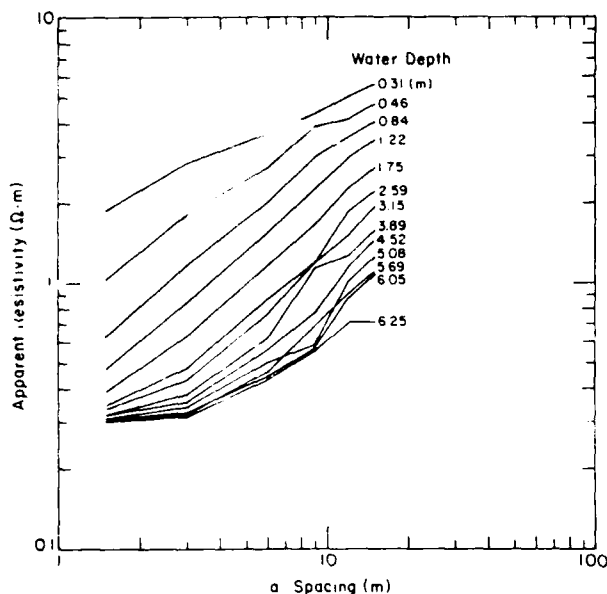


Figure 6. Influence of depth of seawater on apparent resistivity. Data were obtained at Eastport, Maine, with a Wenner array on the seafloor.

with variables being water depth and electrical properties of the seafloor. A conservative value of $20 \Omega \cdot m$ was assigned to the bedrock so as to examine our limits of bedrock sensitivity. The modeling results are shown in Figure 3, with data from field observations made during the tidal cycles shown in Figures 4 and 5. The curves all have the same range of values and show decreasing sensitivity to the seabed with increasing water depth. For a 3-m water depth, an a spacing of at least 25 m is required to give ρ_a values above the resistivity value of the sand. Figure 4 shows good agreement between field data and model at the Kittery site for low and high water limits.

Similar variations in resistivity with water depth also occur in data collected with a bottom cable (Fig. 6). In addition to the orderly decrease in sensitivity to the seabed with increasing water depth seen in the Kittery data and model and in the Eastport data for the floating cable (Fig. 3-5), the bottom cable also shows a noticeable decrease in sensitivity to water depth at the closely spaced electrodes. No modeling of bottom cable responses was attempted, although it is apparent that a bottom array is also very sensitive to water depth (compare $a = 10$ m in Fig. 5 with that in Fig. 6) in areas of shallow water. Therefore, on the basis of these results, the availability of models for interpreting data only from surface arrays, and the anticipated damage to an array dragged on the

seabed, we decided to use a floating cable for our surveying in shallow coastal waters.

New Haven Harbor: bedrock studies

The site at New Haven Harbor was selected because of the substantial information available on depth of bedrock and on the properties and distribution of sediments. The information is based on drilling and sampling done as part of a U.S. Army Corps of Engineers (1981) study. A sample of the contoured depth to bedrock data is shown in Figure 7.

The surveys were conducted near the central part of the harbor. The outcrop resistivity values (Table 1) were obtained along the shore and are similar to the values for the Maine sites. The electrical properties at all the sites are similar to those expected in some coastal permafrost settings, particularly if the contact between ice-free and ice-bearing materials is not gradational.

A mathematical model (Mooney et al. 1966) was first used to investigate the theoretical effect of variations in depth to bedrock for resistivity and depth parameters expected in New Haven Harbor. The two models in Figure 8 show that for fixed water depths of 6 and 7 m, a variation in total depth to bedrock of 47 m will result in only a $1 \Omega \cdot m$ change for a surface Wenner array with $a = 50$ m. This fact, coupled with the large influence of water depth on ρ_a , required that good water depth control be maintained during a survey.

Several survey lines were run using the Wenner marine cable, one of which is shown in Figure 9. This profile was made along the west side of the channel where water depth was fairly constant at 6 ± 0.3 m. Because the water depth variations are small, the resistivity profile can be compared directly with observations on depth to rock from the Corps of Engineers survey. The resulting correlation shown in Figure 9 is very good. The range of ρ_a is approximately $0.8 \Omega \cdot m$ for a total depth to bedrock change of about 40 m, which agrees with the prediction of our model data shown in Figure 8.

These preliminary observations and modeling demonstrated the utility of simple dc resistivity equipment for mapping resistive seabed features in shallow coastal waters. The low-power Wenner system provided data that agreed qualitatively with variations in the position of the top of bedrock at depths as great as 50 m below sea level. The importance of having good control on water depth in shallow water surveys was also illustrated.

The electrical properties of these sections were

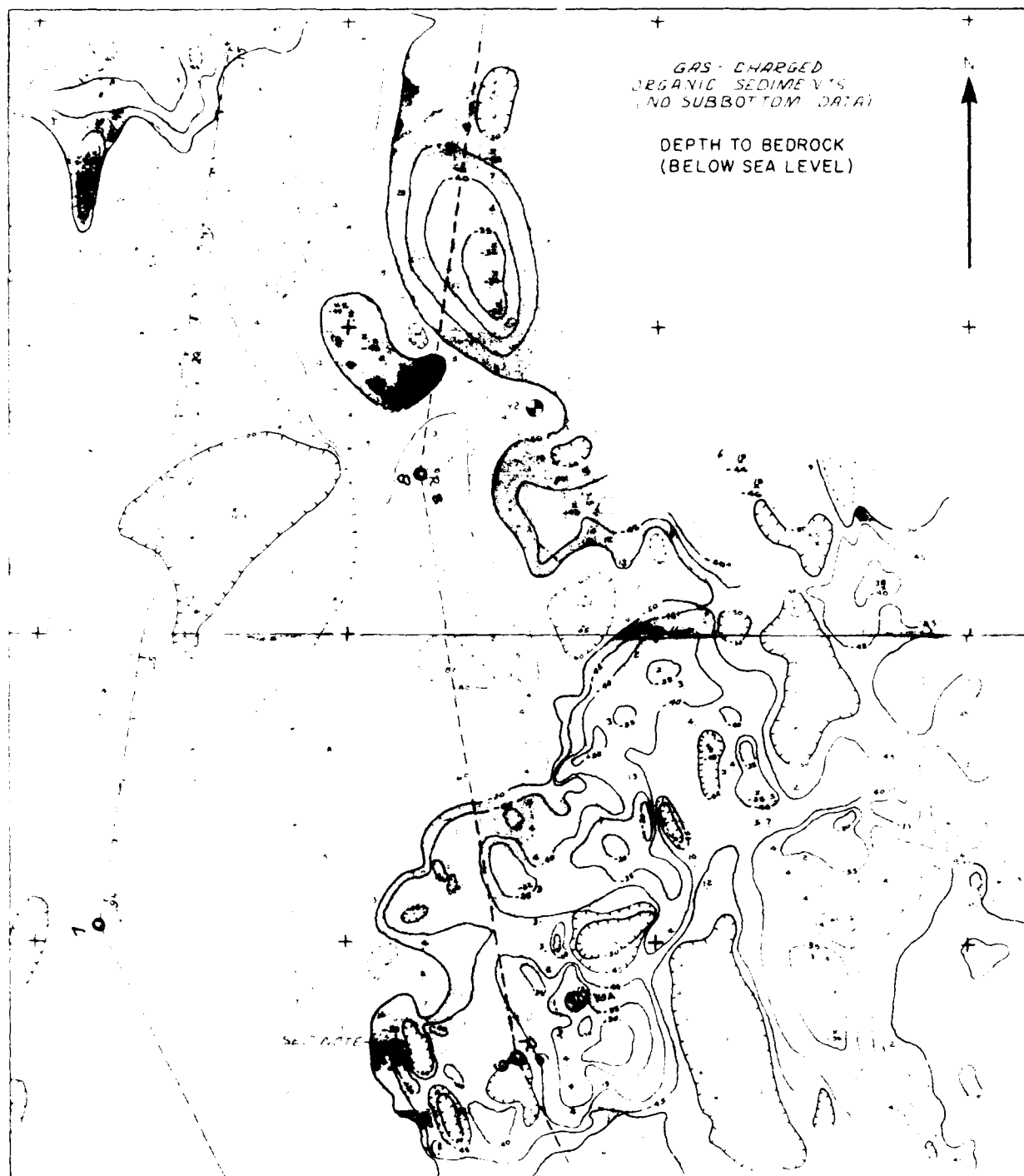


Figure 7. Example of depth to bedrock data used for control in the New Haven harbor study (from U.S. Army Corps of Engineers 1981).

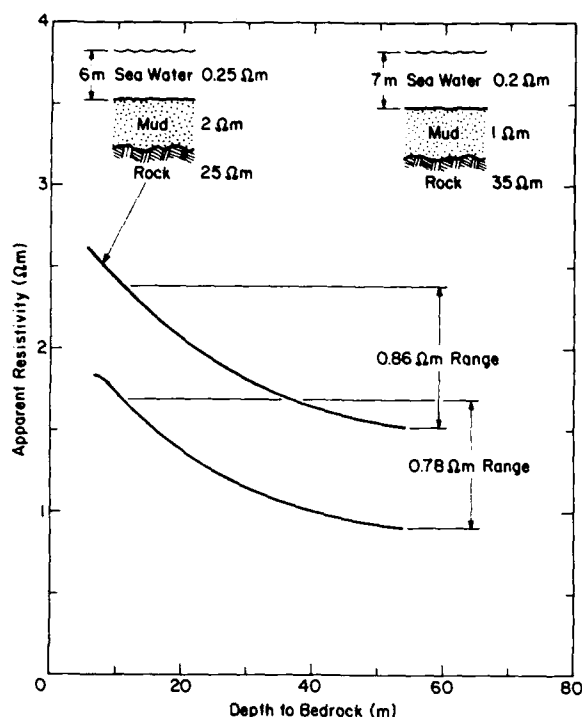


Figure 8. Two models showing the range in resistivity values expected for a survey in New Haven Harbor for an a spacing of 50 m.

within the range of those expected in some areas with ice-bonded subsea permafrost. In some cases ice-bonded permafrost will be more variable with gradational contacts and layered structure. This naturally will make detection and mapping more difficult for the dc method, as it would for any geophysical technique. These positive results led us to the permafrost studies reported in the following section.

Prudhoe Bay

The rates of coastal erosion and associated modification of the cold terrestrial permafrost vary greatly along the Beaufort Sea coastline and depend on material type, coastal relief and exposure to the sea. Three sites were selected for this study in the Prudhoe Bay area and are shown in Figure 10. The Prudhoe Bay area has low coastal erosion rates compared to more western segments of the Beaufort Sea, where rates commonly exceed 5 m/yr (Reimnitz et al. 1985). Rates in Prudhoe Bay are closer to 1–2 m/yr and are probably lower than other segments of the coast because of the coarser material and lower ground ice volumes in the upper part of the permafrost section. Infiltration of sea water can rapidly influence electrical properties of coarse-grained material if voids are not ice-filled. In general, chemical modification by salt should be much less rapid in fine-grained than in coarse-grained sediment.

The soundings on land were all made asymmetrically by expanding the electrodes in one direction parallel to the water's edge at a spacings of 0.5, 1, 2, 3, 4, 5, 7, 10, 20, 30 and 50 m. The marine resistivity data were gathered every 25 m along profiles at fixed a spacings on lines normal to the coast. The offshore a spacings commonly used were 3, 6, 9, 12, 15, 30 and 46 m. In Figure 11 contours of equal values of apparent resistivity are mapped as a function of distance and a spacing. The position of important features such as the coastal bluff, beach and shoreline are noted. Inserts with expanded scales in the figures illustrate the rapid changes in resistivity seaward of the coastal bluff. No insert was constructed for site 3 since changes landward were gradual.

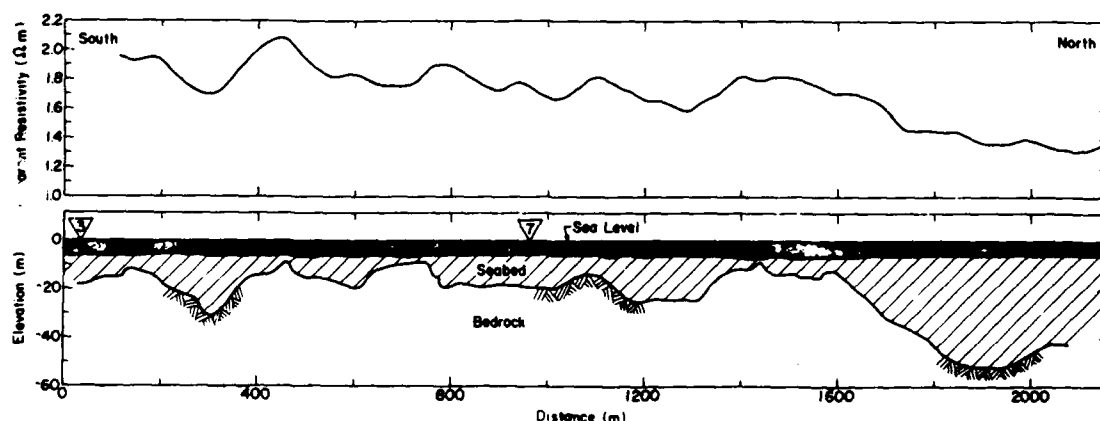


Figure 9. Wenner resistivity profile obtained along the west side of the channel in New Haven Harbor at a 50-m a spacing.

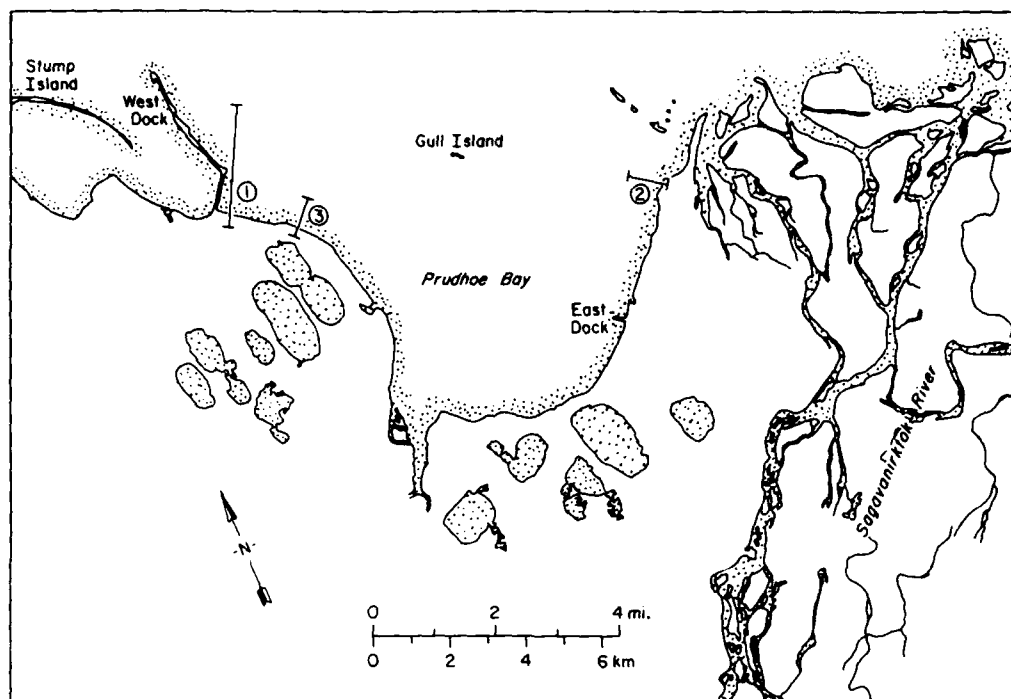


Figure 10. Map of the Prudhoe Bay area showing the location of our study sites and the orientation and length of our resistivity profiles.

Site 1

This site (see Fig. 10) is situated several hundred meters east of the West Dock in Prudhoe Bay. It has a low bluff about 1.5 m high and a very narrow 1- to 3-m wide beach. The fresh nature of some of the exposures suggests active erosion. Only a small increase in sea level is required to bring waves in direct contact with the bluff. This low bluff and the adjacent terrain are easily overtopped during storms, as indicated by the large amount of driftwood found more than 100 m inland.

Direct observations reported by Baker (1987) of the depth to the top of ice-bonded permafrost offshore along one control line are shown at the top of Figure 11a. This line provided ideal control for the marine resistivity study, and was based on drilling and probing. Water depth data included in all the profiles were collected during our resistivity survey.

Site 2

This site is about 3.7 km northeast of the East Dock in Prudhoe Bay (see Fig. 10). The tallest coastal bluffs occur here (Fig. 11b, top), ranging from 2 to 3 m in height. The beach is about 6 m wide and is covered with sod blocks that slumped from the tundra surface. The bluff face is actively erod-

ing, with large blocks collapsing over fresh exposures. Wave overtopping of the bluff appears to be very limited, with only minor changes in the vegetation patterns near the bluff crest attributable to salt spray. The materials exposed in the bluff are silty sands, which seem similar to the exposed sediments for all sites. No information on subsea permafrost was available for sites 2 and 3; the subsurface interpretations shown in Figures 11b and 11c are the results of computer modeling and will be discussed below.

Site 3

This site is approximately 2 km east of the West Dock (see Fig. 10). This location is different from the previous sites in that it lacks a coastal bluff (Fig. 11c, top). The beach formed between two points of land and grades into the low-lying adjacent tundra. Overtopping of the beach and inland flooding of the tundra is extensive because of the low elevation of the tundra surface. Driftwood can be found more than 200 m inland.

Land observations

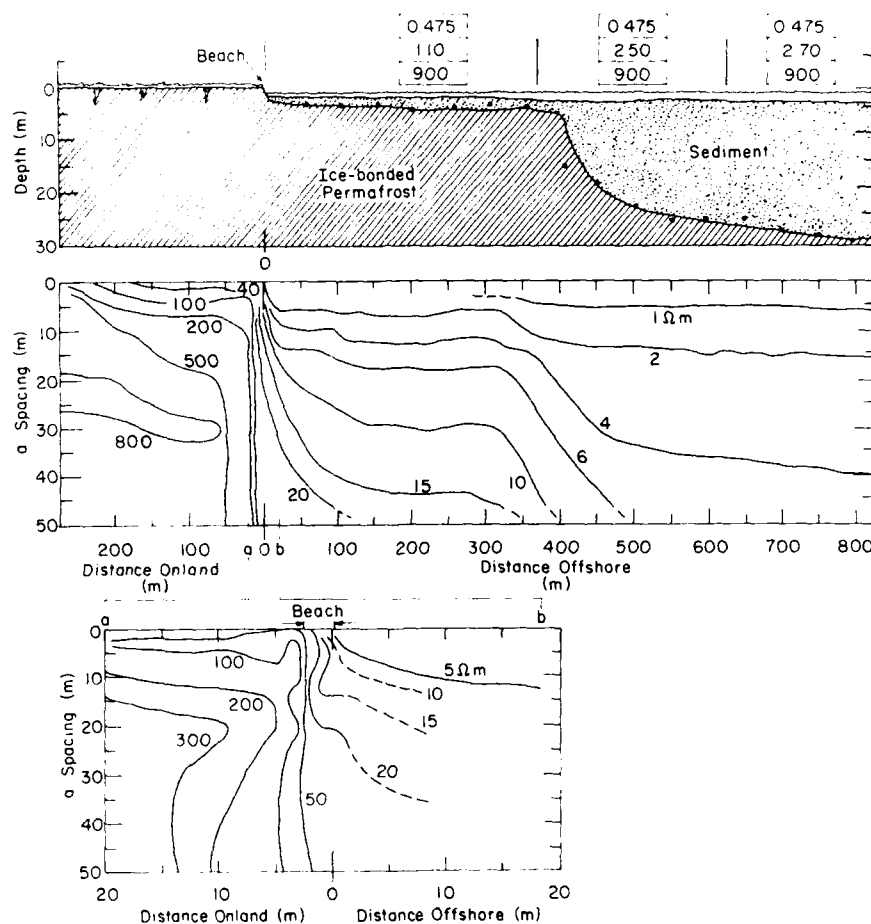
There are some unique features in the on-land resistivity data that appear related to surface relief, beach width and potential for surface flood-

ing. The greatest resistivities were observed at site 2 (Fig. 11b), which had the highest bluffs and the least physical indication of flooding or other inland disturbance. A maximum apparent resistivity of $2800 \Omega\cdot\text{m}$ was observed 65 m inland of the bluff. The high values and the horizontal disposition of the contours suggest that site 2 has had the least modification. In contrast, sites 1 and 3 show the influence of past flooding by significantly lower values of near-surface resistivities and the seaward sloping of the resistivity contours. Near-surface resistivities at site 3 are less than $6 \Omega\cdot\text{m}$ at distances more than 175 m inland from the inner edge of the active beach, a distance that driftwood

and other debris indicates is the inner limit of most recent flooding. The topography in this area suggests that coastal flooding may have occurred at this site for many years. Values greater than $500 \Omega\cdot\text{m}$ are not found at depth until the inner limit of flooding is exceeded. At the more easterly site 2, the $500\text{-}\Omega\cdot\text{m}$ values correspond with the tall bluffs and higher-elevation tundra surface that mark the inner limit of flooding.

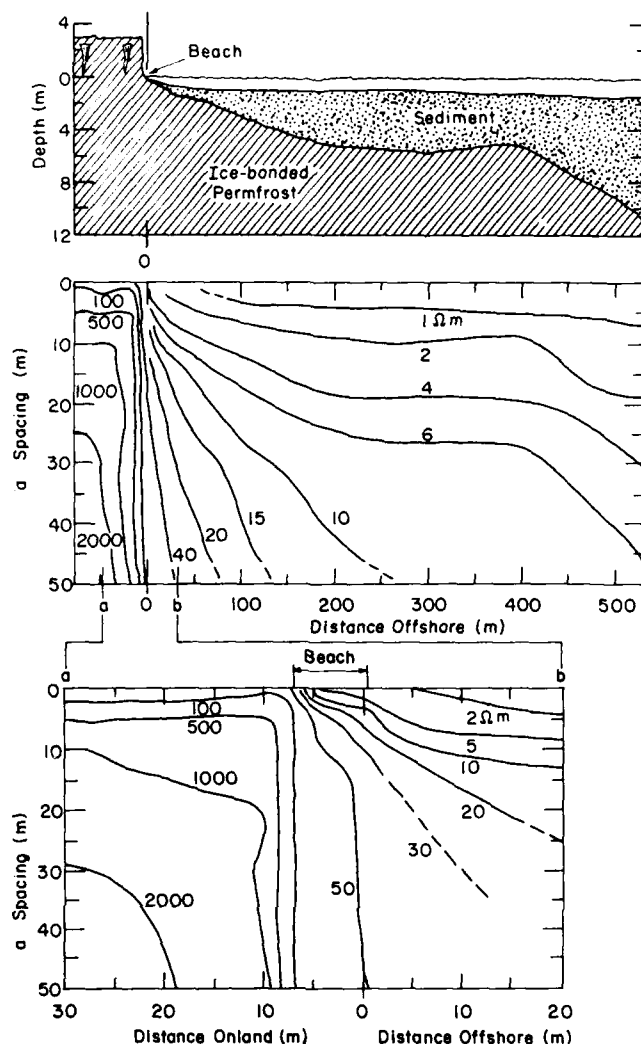
Seaward observations

There are some common patterns in all data from seaward of the coastal bluffs. No apparent resistivity values greater than $100 \Omega\cdot\text{m}$ were ob-



a. Site 1. Contoured data for an expanded segment of the line are shown in the lower part of the figure. The position of the top of ice-bonded permafrost (after Baker 1987) is shown in the upper part of the figure as a solid line. The computed depth to the top of ice-bonded permafrost (shown by dots) was calculated using the three-layer resistivity models at the top of the figure (resistivity values in ohm-meters).

Figure 11. Contoured apparent resistivity data in Prudhoe Bay.



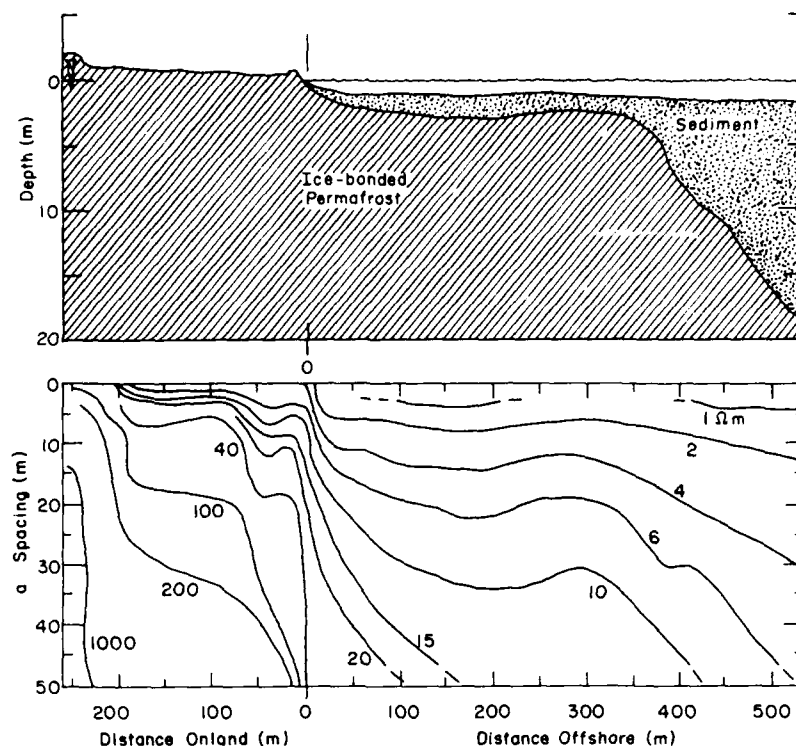
b. Site 2. Water depth, height of the coastal bluff and computed depth to the top of the ice-bonded permafrost are shown in the cross section in the upper part of the figure. Contoured data for an expanded segment of the line that includes the beach are shown in the lower part of the figure.

Figure 11 (cont'd). Contoured apparent resistivity data in Prudhoe Bay.

served at even the largest a spacings. The values and trends were similar between the bluffs and the water edge, with no values at the water edge greater than $50 \Omega \cdot m$ at 50-m a spacings; most values were less than $40 \Omega \cdot m$.

Variations in water depth along the study lines were usually less than 1 m , the total depth never exceeded 2 m , and the water's resistivity was always about $0.47 \Omega \cdot m$. The contoured data of Figure 11a demonstrate that these parameters were not sufficient to mask resistivity variations at depth.

For example, the larger change in resistivity at depth in Figure 11 occurs in a zone between 300 and 400 m where there is less than a 0.5-m variation in water depth. This small change in water depth cannot account for the more than $6\text{-}\Omega \cdot m$ resistivity change seen across the zone at an a spacing of 46 m , since our earlier field observations (Fig. 5) and theoretical considerations have shown that a 0.5-m change in water depth would account for a variation of less than $1 \Omega \cdot m$. The resistivity changes seen at the small a spacings ($3\text{--}6$



c. Site 3. Water depth, coastal relief and computed depth to the top of ice-bonded permafrost are shown in the upper part of the figure.

Figure 11 (cont'd).

m) are expected for the small changes in water depth (Fig. 11a and c).

The relatively large variations in resistivity with depth and the configuration of the contours correspond with the shape of the top of ice-bonded permafrost observed in the control section of Figure 11a. However, the anomaly in the resistivity data is shoreward of the break (the sharp increase in permafrost depth at 400 m) in the control data. This discrepancy may be caused by our resistivity line being slightly east of the control line, but is more likely attributable to limitations in resolution of the technique itself, which are discussed below. The marine resistivity data at the other sites (Fig. 11b and c) also show similar breaks, which are taken to indicate a sudden increase in depth to the top of the ice-bonded permafrost. The offshore location of the breaks occurs in the zone where water depths are approximately 1.5 m.

There is a noticeable gradient in all the resistivity data that fall within about 200 m of the beach and appears to reflect changes in the electrical properties of permafrost. We believe this to be caused by warming in the marine environment.

Apparent resistivities at our sites fall below 20 $\Omega \cdot m$ within the first 100 m of the shore at 46-m a spacings.

Modeling

Numerical interpretation of the offshore apparent resistivity data using Baker's (1987) depth profile for site 1 (Fig. 11a) achieved a good fit with three-layer models. We needed 3 three-layer models to interpret the entire line; they are shown, along with the calculated position of the top of ice-bonded permafrost, at the top of Figure 11a. The first layer resistivity was held constant at the measured value of 0.475 $\Omega \cdot m$. Second layer resistivity was increased with water depth and distance from shore. A resistivity of 1.1 $\Omega \cdot m$ was used when water depths were 1.5 m and less, 2.5 $\Omega \cdot m$ for the 1.6- to 1.8-m range, and 2.7 $\Omega \cdot m$ for depths 1.9 m and greater. These resistivities seem logical because of the possibility of salt enrichment of the bed sediments in the shallow water zone when salt is rejected during formation of the sea ice. At greater water depths there would be more chance for mixing and freshening of the bed sediments.

The only significant error in interpreted depth is at the 400-m station. This occurs at the one point where the permafrost depth drops suddenly and the Wenner array would have spanned, and integrated the resistivity over, this sudden discontinuity in layering depth. The greatest change in depth occurs over a 50-m distance, which approximately equals the largest value of a used and is about 33% of the total array length. At all other stations, horizontal changes in layering are sufficiently small to allow this one-dimensional sounding procedure to provide good resolution for this two-dimensional cross section.

Apparent resistivity data for the other two sites (2 and 3) were interpreted using the model resistivity values and depth relationships developed for site 1. The calculated position of the top of ice-bonded permafrost is shown in the upper parts of Figures 11b and c. These models are not greatly influenced by variations in resistivity of the third layer. Resistivity of the ice-bonded permafrost can be varied from 200 to 1000 $\Omega\cdot\text{m}$ without significant change in the calculated depth to the top of this layer. However, calculated depths of the ice-bonded permafrost are extremely sensitive to changes in the resistivity of the second layer. For example, where the observed depth to the top of the ice-bonded permafrost is 22 m below the seabed, a $\pm 0.5\text{-}\Omega\cdot\text{m}$ variation in the resistivity providing the best fit can cause a $\pm 6\text{-m}$ variation in layer thickness. Even though first-layer parameters are also important, they are not a problem since they can be directly measured at the time of a survey.

The resistivity values obtained for the frozen

and unfrozen sediments allow us to evaluate the ability of a Wenner array with a maximum electrode spacing of 50 m to perform over water that exceeds the depths encountered here. This is illustrated in Figure 12, which shows the apparent resistivity calculated for a 50-m a spacing as a function of water depth in cases where ice-bonded permafrost with a resistivity of 900 $\Omega\cdot\text{m}$ is beneath three sediment ($2.5\text{-}\Omega\cdot\text{m}$) depths of 3, 7 and 20 m. The curves show that, beyond about a 7-m water depth, there is little sensitivity to the total depth of permafrost. This was not a problem in the Prudhoe Bay study since water depths did not exceed 3 m.

SUMMARY AND CONCLUSIONS

Using dc resistivity data from an arctic coastal setting, we have illustrated the impact of marine inundation on cold permafrost formed on land. The floating array ($a = 50\text{ m}$) also provided a tool for measuring the electrical properties and distribution of permafrost in shallow coastal waters where ice-bonded permafrost may not be more than 30 m below the seabed and where water depths do not exceed 6 to 7 m. The technique also has application to subsea bedrock investigations under certain coastal conditions. Our observations indicate that in shallow coastal waters (less than about 7 m), a Wenner seabed cable would offer no advantage as both floating and seabed cables are about equally sensitive to changes in water depth. However, bottom cables should have greater sensitivity to seabed changes in deeper water.

Apparent resistivity observations for Wenner electrode separations up to 50 m made along several cross sections extending from land into Prudhoe Bay have some similar characteristics: 1) resistivities greater than 20 $\Omega\cdot\text{m}$ were not observed more than 100 m from shore, 2) maximum resistivities at the water's edge were around 50 $\Omega\cdot\text{m}$, 3) resistivities greater than 100 $\Omega\cdot\text{m}$ were not found seaward of the coastal bluffs, and 4) resistivities just inland of the bluff can increase above the seaward values by an order of magnitude. Modeling indicates that real resistivities for the sediment over ice-bonded permafrost ranged from 1.1 to 2.7 $\Omega\cdot\text{m}$ and that the permafrost may range from 200 to 1000 $\Omega\cdot\text{m}$.

Resistivity contour patterns and modeling results correspond well with the drilling and penetrometer observations of Baker (1987); thus, this geophysical approach has been useful in this geo-

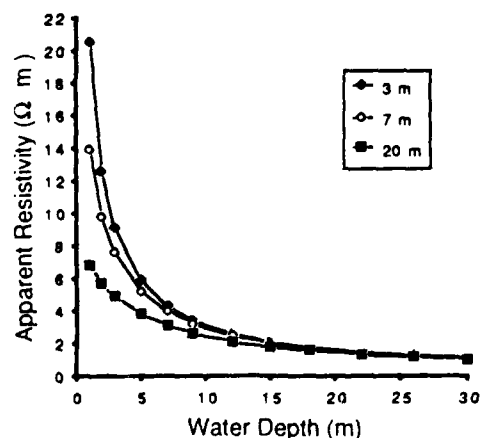


Figure 12. Model resistivity data (50-m a spacing) for various water depths in cases where ice-bonded permafrost is 3-, 7- and 20-m depths beneath the seabed.

logical setting and appears to have applications for scientific and engineering investigations, such as offshore pipeline design and routing. The contours and modeling suggest that a rapid increase in the depth to the top of ice-bonded permafrost seen at the control site also occurs along other study lines in Prudhoe Bay. The position of this zone of noticeable increase in depth to the top of permafrost seems to correspond approximately with the 1.5-m water depth. The data on resistivity variations within 200 to 300 m of the coastline may also provide useful information on historical erosion rates.

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